BULLETIN No. 90.

U. S. DEPARTMENT OF AGRICULTURE,

OFFICE OF EXPERIMENT STATIONS,

A. C. TRUE, Director.

Irrigation Investigations, Elwood Mead, Expert in Charge.

IRRIGATION IN HAWAII

BY

WALTER MAXWELL, PH. D.,

Director and Chief Chemist, Hawaiian Experiment Station.

WASHINGTON:

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Office of Experiment Stations,
Washington, D. C., November 30, 1900.

Sir: I have the honor to submit for publication as Bulletin No. 90 of this Office an article on irrigation in Hawaii, by Walter Maxwell, Ph. D., for a number of years director of the experiment station maintained by the Hawaiian Sugar Planters' Association. This article has been prepared in connection with the irrigation investigations of this Office. It discusses the climatic, soil, and other conditions as affecting irrigation in Hawaii and gives the results of irrigation experiments, especially with sugar cane, carried on by the author for a number of years. It brings out some of the most interesting phases of irrigation problems in that Territory, and will form a basis for further investigations of this subject there.

Respectfully,

A. C. True,
Director.

Hon. James Wilson,
Secretary of Agriculture.

CONTENTS.

ILLUSTRATIONS.

PLATES.

TEXT FIGURES.

IRRIGATION IN HAWAII.

INTRODUCTION.

The precipitation of atmospheric moisture is very uneven and irregular over the surface of the earth. There are zones that are marked by annual deluges, and there are vast areas upon which rain rarely falls. These rainless areas are not confined to conditions peculiar to specific latitudes, but are found in the tropical regions of India and Africa, over the wide plateaus of North America, and in other localities having widely varying climatic conditions.

The regions of small rainfall are very generally distinguished by lands of great natural fertility. This is due largely, on the one hand, to the absence of great rains that leach out the elements that feed plants, and, on the other hand, to the relative absence of crops, which results from lack of rain. Among the most productive tracts upon the earth to-day are regions that were naturally arid, but which have been rendered productive by irrigation. These tracts include the Punjab and other vast districts of India, the great basin of the Nile in Africa, and large semiarid areas that have more recently been brought under cultivation in the middle and western United States.

The failure of the natural rainfall to produce crops may be due to the insufficiency of the total precipitation, as in regions in India, Africa, and other lands, where it does not aggregate 10 inches per year; or it may be due to the seasonal distribution, as in other parts of India and Africa, in northern Queensland, and some of the Pacific islands, where a heavy and almost the whole precipitation takes place within two or three months. In speaking of the agriculture in parts of the Himalayas, Mr. Buckley[1] says: "Where the rainfall varies from 50 to as many as 100 inches in the year, crops grown on the terraces in the mountains are matured in the dry season by artificial irrigation." In some localities in northern Queensland the annual rainfall reaches and exceeds 100 inches, yet the sugar-cane crop has to linger through an annual arid period which greatly reduces the yield, while upon the Pacific islands of Hawaii, despite the winter rains, many of the most fertile lands would be useless without the prevailing practice of irrigation. Irrigation, consequently, is playing an increasingly important part in modern intensive agriculture.

[1] Irrigation Works in India and Egypt, R. B. Buckley. London, 1893, p. 1.

The history of irrigation covers methods of applying water to crops, including the crudest efforts of the peasant and the great systems executed by governments or corporations, such as are in operation in India, the United States, and in the valley of the Nile. Certain of those systems are vast, and have been instituted under the pressure of meeting great emergencies. To-day India is using irrigation upon a stupendous scale in grappling with the calamity of famine.

Economic irrigation requires the consideration of physical laws which were unknown to the authors of primitive methods, and which have not been generally observed in establishing the huge systems of irrigation already mentioned. Some of the physical laws which underlie any rational practice in the application of water to crops are briefly considered in the following paper.

EVAPORATION OF MOISTURE FROM WATER SURFACES AND SOILS.

The movement of moisture is constantly going on. The simplest evidence of this movement is seen in rainfall and in the evaporation from water and soil surfaces.

The factors that have been given the greatest prominence as exercising a controlling action upon evaporation from soil and from the surface of water are the temperature and the relative humidity of the air. This view is amply sustained if the examination is confined to the action of these factors during the extreme seasons of the year. There is no question concerning the greater evaporation of moisture from soils and waters during the months of summer, when temperatures are high, and the amount of atmospheric moisture is also relatively smaller than during the cold season, when the temperature is lower and the humidity of the air greater. This is demonstrated in many localities by the excess of water that accumulates within and upon the soil in winter and the droughts that obtain in the summer. There are localities and regions, however, that are so fortunate as to have the greatest rainfall during the season of greatest evaporation and consequently of greatest plant growth. Setting aside the differences concurrent with the seasons and confining observations to the relative actions of the several factors during the months of summer, it is then found that the temperature of the air and the amount of moisture that it contains are not the most dominant factors in the control of evaporation. As already said, they are factors, but their combined effects do not compare with the effects of wind. Not only in the matter of irrigation, but also in the location and exposure of reservoirs this fact is of leading importance. In view of this the writer carried out a series of evaporation determinations by means of evaporators, at the same time keeping a record of the temperature and relative humidity of the air. These observations were made as a part of a study of the factors that control the rational irrigation of the

sugar cane on the Hawaiian islands. The form of evaporator used was a small galvanized iron pan, 1½ inches deep and having a superficial area of 120 square inches. The evaporator was placed under the covered stand where the meteorological instruments were located and between the dry and wet bulb thermometers, thus having the same protection from the sun and the same exposure to the wind as those instruments. At 7 o'clock on the morning of the first day 500 grams of water were weighed into the evaporator, and at the end of each twenty-four hours the weight was retaken and recorded and the volume made up again to 500 grams. These observations were made daily throughout one year. A second evaporator similar to the first was placed in a barn 30 feet distant from the other. The large doors of the barn were kept open day and night to allow of air circulation, but any violent air movement was rigidly guarded against. The purpose was to secure the same conditions of temperature and humidity of the air as those surrounding the evaporator placed outdoors, but to eliminate the factor of wind. The data furnished by the two evaporators were taken and recorded in the same manner and with the corresponding readings of the thermometers. The results of these observations, covering a period of two hundred and seventy days, reduced to monthly averages, are given in the following table:

Relative evaporation from water surface exposed to the wind and protected from the wind.

Month.	Exposed to the wind.			Protected from the wind.		
	Temperature of air.	Humidity of air.	Evaporation.	Temperature of air.	Humidity of air.	Evaporation.
	°F.	*Per cent.*	*Per cent.*	*°F.*	*Per cent.*	*Per cent.*
April	74.4	77.4	28.5	78.7	77.4	11.7
May	76.0	80.2	27.2	80.3	80.2	11.3
June	77.0	83.6	22.5	81.3	83.6	10.1
July	78.3	77.3	25.8	83.0	77.3	12.1
August	78.7	73.8	30.0	82.4	73.8	12.5
September	76.8	80.4	24.3	80.6	80.4	10.0
October	75.3	80.1	23.5	78.8	80.1	9.2
November	71.0	83.2	23.3	74.1	83.2	9.4
Average	75.9	79.5	25.6	79.9	79.5	10.8

A relation may be noted between the temperature and humidity of the air and the amounts of water evaporated, but the important fact revealed by the table is the constant and great difference in the amount of water evaporated from the two pans. The total amounts of water lost during the eight months by the exposed and protected evaporators were, respectively, 33,480 grams and 14,175 grams.

The outdoor evaporator lost 136 per cent more water than the indoor evaporator. This vast difference is wholly due to the action of the wind, to which the former was exposed, and it occurred in spite of the fact that the indoor temperature was uniformly 4 degrees higher than the outdoor temperature.

The differences in the amounts of water given off by the outdoor evaporator on different days bear some relation to the differences in the temperature and humidity of the air. They are too great, however, to be accounted for by those factors alone; they were, in fact, largely due to different velocities of the wind. By way of proving this, we make use of the data recorded during the month of November. During the first ten days of that month the average daily evaporation, under the constant action of the northeast trade wind, was 33.7 per cent. During the following eight days, when the wind direction was south and the air was almost still, the average evaporation was only 13.2 per cent. During these eighteen days the maximum evaporation under a very high wind reached 41.2 per cent, while upon another day, no motion of the air being observed, the evaporation was only 8.1 per cent. In the course of these twenty days the temperature variations were very small.

From the determinations that have been recorded it may be seen that the movement of the air is the paramount factor in controlling the rate of evaporation from water and soil surfaces. Soils whose surfaces are exposed to the action of strong driving winds will give up more moisture, and will therefore need more water, than areas in sheltered locations. Water surfaces exposed to the sweep of the wind lose heavily by evaporation. Economy of water therefore dictates that reservoirs be built so as to have the greatest depth and the least surface, and that they be located so as to be sheltered from the direct action of prevailing strong winds.

TRANSPIRATION OF MOISTURE BY VEGETATION.

The volume of water evaporated from the soil and the volume transpired by the plant during its growth are the controlling factors in determining the total water required in the production of a crop, and therefore the quantity of water to be supplied by irrigation.

Water enters very largely into the structure of all living organisms. It is not only the agent which makes possible the mobility of other constituents of the plant, conveying them from one location to another, but it enters in large proportion into the structure of the organism itself. Consequently plants and trees at all times hold a great volume of water, the supply of which is constantly replenished by the water taken up by the roots and as constantly depleted by the moisture given off into the air by means of transpiration. It is these quantities that we require to know something definite about.

Experiments with the sugar cane to determine these quantities have been carried on by the writer at the Hawaiian Experiment Station. The specific purpose was to determine the volume of water required by the cane at different stages of its growth and to come at a rational mode of irrigation. The experiment was carried out as follows: Two

tubs were used, having perforated bottoms, over which pieces of linen were laid to prevent the soil from going through or filling up the perforations. One hundred and twenty-five pounds of similar soil was put into each tub. The tubs were then set into galvanized-iron pans containing water. The water was kept up to a certain level, which level was slightly above the point of contact between the soil in the tubs and the water in the pans. The pans were carefully covered with moisture-poof oilcloth to prevent any escape of water excepting through the tubs. The volume of water taken up by the soil in the tubs and given off was daily measured and recorded and an equal volume restored to the pans. The volume of water that the soil could absorb and contain—that is, the measure of its absorptive power—was 48.2 per cent of its own weight. In tub No. 2 three pieces of sugar cane were planted when the experiment was begun, and nothing in tub No. 1, after which the water given off by each tub was daily recorded for the following six months. During the first twenty-six days the two tubs gave off like volumes of water, each one evaporating during that period 14,220 grams, or 31 pounds. After the twenty-sixth day tub No. 2, in which the cane was planted, began to give off more than tub No. 1, containing soil only. At the end of seven months the relative volumes of water given off by the tubs were:

	Grams.
Tub No. 2	159,550
Tub No. 1	80,240
Difference	79,310

The water transpired by the growing cane during the period stated was thus 79,310 grams, or 174.5 pounds, and was distributed as follows:

Water transpired by sugar cane.

Time of observation.	Age of cane.	Transpiration.	Time of observation.	Age of cane.	Transpiration.
	Months.	*Grams.*		*Months.*	*Grams.*
May	1	860	August	4	19,800
June	2	6,500	September	5	20,050
July	3	11,000	October	6	21,100

From these data we learn the weight of water evaporated per given weight of soil during a given period of time. More important, we also see the volume of water transpired by the growing cane during the several months of its growth. We note the increasing volume required by the cane during the stages of growth and increase in bulk, and these observations are a clear and definite indication of the amount of water required in irrigation. When the cane plant is young its needs are small in comparison with its requirements at later stages of growth, and to apply the same volume during the early months that is demanded

later is not only sheer waste, but entails damage to the young cane and loss to the soil. However, as explained later (p. 46), the increased evaporation from the soil while the plants are too small to shade the soil to any extent in a measure counterbalances the decreased transpiration in this stage.

The weight of the cane grown in tub No. 2 by the consumption of 79,310 grams of water was 568.9 grams of water-free material, consisting of roots, 31.8 grams; stems, 53.9 grams; leaves, 483.2 grams. These figures show that in order to form 1 pound of water-free substance the cane organism transpired 147.8 pounds of water.

Attention is due to the behavior of the transpiring plant under the influence of given physical conditions. It was previously shown that the evaporation of water from soil and water surfaces was relatively very small in the absence of wind and during hot, sultry weather. This was by no means the case with the cane plants, as the following figures show:

Effect of weather conditions on evaporation from the soil and transpiration by sugar cane.

Date.	Number of days.	Character of wind.	Evaporation from soil.	Transpiration from plant.
			Grams.	*Grams.*
June 10 to 23	14	NE. trade	5,700	1,550
June 23 to July 7	14	SSE. calm	3,200	3,300

These results were secured while the cane was still very young and the transpiration small. Similar results were observed repeatedly during the period of the plants' growth. The explanation lies in the fact that, although the hot, sultry weather, which obtains during the prevalence of the south wind has but a small effect upon water evaporation, it provides the physical conditions conducive to rapid plant growth. With the increased plant growth follows the vastly increased transpiration.

At this place may be stated the action of certain chemical elements upon the rate and volume of transpiration by the cane. On September 20 it was noted that the cane in tub No. 2 was looking yellow and in a reduced state of growth, and that the daily volume of water transpired had very largely fallen off. This change was believed to be due to want of available nitrogen in the soil, it having been shown by previous analysis that, while all other required elements were present in abundance, the nitrogen content was unusually small. Consequently nitrogen, in the form of nitrate of soda, was dissolved in the water that was being absorbed by the cane. On September 24 the cane was transpiring only 500 grams of water daily. Two days after the addition of the nitrogen to the water the leaves began to take on

a vigorous appearance again and the volume of water transpired increased until it became more than double on the sixth day, when the cane stood up in full vigor and the yellow color was giving way to a deep green. At the end of October the transpiration fell off again, running down to only 400 grams daily, when a second quantity of nitrate of soda was put in the water. The result was practically the same as in the first test. The following table gives the details of the two tests:

Effect of nitrate of soda on transpiration of moisture by plants.

First test.		Second test.	
Date.	Transpiration.	Date.	Transpiration.
	Grams.		*Grams.*
September 24	500	October 31	400
September 25	600	November 1	600
September 26	700	November 2	700
September 27	900	November 3	700
September 28	1,200	November 4	700
September 29	1,100	November 5	800
September 30	900	November 6	800
October 1	900	November 7	800
October 2	900	November 8	800
October 3	900	November 9	800

These tests not only display the part played by the element nitrogen in the plants' growth and the consequent transpiration of moisture, but they also afford a clear illustration of the relations of fertilization to irrigation—relations which should receive the most careful consideration in all field work. In time of prolonged drought in districts of small or irregular rainfall the application of fertilizers that stimulate growth and transpiration is not advisable, since such agents cause a rapid exhaustion of soil moisture, after which the crop goes back again, its condition being finally worse than had it not been fertilized. But after a rain following a period of drought nitrogen should be applied at once to help the crop recover lost time.

POWER OF SOILS TO ABSORB AND RETAIN MOISTURE.

It is now necessary to consider the properties of the soils themselves, and to note the nature and differences of those properties in different soils and the behavior of different soils in practical irrigation.

Before making any explanation of the causes attention is called to the fact of the great variation in the power of soils to absorb and retain moisture. In the discussion of this point conditions, examination, and results relating to the Hawaiian Islands only are considered, and particularly investigations which have had special reference to the irrigation of sugar cane in these islands. Instead of giving a lengthy and detailed description of the means by which such examinations are

carried out, attention is called to an illustration (fig. 1) of the apparatus used in the work, which almost explains itself. The labeled cylinders are of a known weight and are filled with soils whose water contents are known and the weight of each is taken. The frame from which the cylinders are suspended is lowered until each cylinder is brought and kept in contact with the water in the trough below. When it is shown by repeated weighings that the respective soils have taken up all the water they can, the weights are recorded, and from these data are calculated their absorptive powers. The cylinders are then kept suspended in the air, the water is removed from the trough,

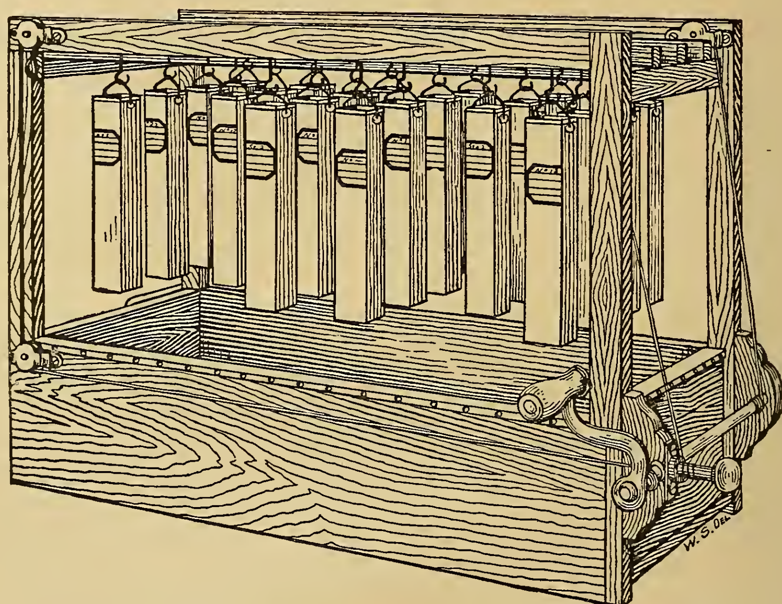


FIG. 1.—Apparatus used in observations on absorption and retention of moisture by soils.

and the cylinders are reweighed at weekly intervals, and from the data of the reweighings the retentive powers of the soils are ascertained.

The following table shows the results obtained. It should be understood that these soils are all of volcanic origin and that they owe their extreme divergencies in physical properties, in the first place, to causes which date from the emission of the lavas from the craters, and, in the second place, to the extreme variations of climatic conditions that exist locally upon these islands. The table expresses, in the second column, the percentage of water absorbed by each soil, in the third column the water retained at the end of one month, and in the fourth column the water finally retained:

Water absorbed and retained by Hawaiian soils.

Sample of soil.	Water absorbed.	Water retained at end of one month.	Water retained at final determination.
	Per cent.	*Per cent.*	*Per cent.*
1	31.8	12.4	2.5
2	50.0	22.9	8.0
3	51.0	19.6	5.5
4	36.5	14.0	5.6
5	59.5	29.3	14.7
6	52.2	23.3	7.7
7	47.0	21.9	8.4
8	46.6	19.7	6.4
9	52.2	20.2	9.4
10	86.4	52.2	28.2
11	72.7	48.4	27.2
12	86.9	51.9	29.2
13	73.7	45.9	25.2
14	73.0	38.6	21.1
15	70.0	42.3	22.1
16	44.3	14.8	5.4
17	46.3	16.8	6.5
18	62.6	29.1	14.3
19	45.2	18.2	8.9

The last weighings were made five months from the beginnings of the tests. It was found that some, in fact most, of the soils were increasing again in weight with increasing dampness of the air in the room.

The causes of the extreme variations in those soils in the matter of their power to take up and hold water are several, but the chief one is the result of local climatic conditions. In localities having small rainfall the growth of vegetation is small, and consequently the amount of vegetable matter which comes from the decay of plants in the soil is also small. In wet districts the opposite is the case. Rainfall means vegetation and copious plant growth means excess of organic matter in the soil as a result of vegetable decay, and excess of organic matter also means an excess of nitrogen in the soil, the nitrogen being a constant component of living and decaying plant organisms. The relation of the amount of nitrogen in the soil to the power to absorb and retain water is shown by the following figures, which give the average of 100 analyses of Hawaiian soils:

Effect of nitrogen on moisture capacity of soils.

Soil samples.	Nitrogen content.	Water absorbed.	Water retained.
	Per cent.	*Per cent.*	*Per cent.*
Average of 50	0.163	44.6	6.2
Average of 50	.647	66.5	19.7

Following the action of organic matter, the next most important factor in determining the power of soils to take up and hold water is the relative amount of clay, or of the elements which form clay, present in the soil.

For the purpose of this discussion we are less concerned with the causes than with the fact that great variations actually exist in the relative powers of soils to take up and hold water. This fact places before us a clear demonstration of the absolute need of first determining the absorptive power of each soil before the application of water.

SALTS IN HAWAIIAN SOILS AND WATERS.

Having considered some of the physical and physiological factors which affect the action and value of water in its relation to the production of crops, we proceed to matters bearing upon its use.

The waters of the Hawaiian Islands are of excellent quality, provided they do not come in contact with the sea inflow or with soils having high contents of salt, due to the overflow of the sea at some earlier period. In some localities, however, contamination by sea water has gone so far that the water is destructive to vegetable life. In most instances the deleterious agent is common salt; in others there is a mixture of common salt with chlorids of magnesium and calcium. The latter are most injurious to plant life and, in lowlands, lying almost level with the sea, where there are no means of getting these salts removed, their impregnation renders the soil useless.

A considerable portion of the water supply for irrigation in the Hawaiian Islands is derived from the underground flow. Ground waters, on account of the considerable proportions of certain highly desirable elements they contain, may be very valuable for application to crops. On the other hand, because of the large amount of substances inimical to plant life held in solution in some cases, they may be quite unfit for irrigation. Numerous instances of the unfitness of such waters for plant use are furnished by other countries, and special examples have been found by the writer upon the Hawaiian Islands.

The salt present in Hawaiian soils and its effect upon sugar cane are shown in the following table:

Salt found in Hawaiian sugar lands, and its effect upon sugar cane.

Sample of soil.	Location.	Salt in soil.	Condition of cane.
		Per cent.	
1	Highlands	0.061	Normal.
2	do	.063	Do.
3	do	.050	Do.
4	do	.059	Do.
5	Lowlands	.129	Not wholly healthy.
6	do	.130	Do.
7	do	.155	Quite healthy and normal.
8	do	.181	Yellow in color.
9	do	.181	Do.
10	do	.460	Small, yellow, stunted.
11	do	.832	Cane white and dying.
12	Sea bluff land	.223	Leaves bleached, cane small.

In soils containing over 0.15 per cent of salt, unless a liberal allowance of some vital element, such as nitrogen, is present to force on the growth, the sugar cane is liable to suffer. A further example is to hand showing the production of three parts of one field which contained different amounts of salt in the soil, the soil in other respects being identical:

Effect of salt upon the growth of sugar cane.

Field.	Salt in soil.	Yield of sugar per acre.
	Per cent.	*Tons.*
First part	0.10	6.0
Second part	.45	1.5
Third part	1.00	0.0

But the salt content of the soil and its action upon the growing crop can be modified by the amount and quality of the water used in irrigation. "Sweet" water can carry the salt down out of reach of the cane roots, but if there is no outlet for the water through the subsoil it will come up again by evaporation to the surface, bringing with it a greater excess of salt to deposit near the roots. "Sweet" soil can bear the use of water containing a considerable amount of salt, but brackish water, added to a soil of appreciable salt content, acts suddenly and rigorously on the cane. An example of the great sensitiveness of the sugar cane, and the ease with which it takes up salt from irrigation waters, is shown in the following record of observations made by the writer:

Effect of salt upon sugar cane.

Condition of water.	Salt in waters.	Salt in cane juice.	Condition of cane.
	Per cent.	*Per cent.*	
Slightly brackish	0.125	0.470	Growing.
Highly brackish	.223	.714	Dying.

In this example the soils contained exactly the same quantities of salt, about 0.15 per cent, which is too high to come in contact with even the slightly brackish water without detriment to plants. The extreme sensitiveness, of the sugar cane to the salt content of waters is made very clear. From our present experience, the danger point should be placed at 0.14 per cent, or 100 grains of salt per imperial gallon.

The following table gives some analyses of Hawaiian waters that are in constant use for sugar-cane irrigation:

Analyses of Hawaiian waters.

Constituents.	Sample No. 1.	Sample No. 2.	Sample No. 3.	Sample No. 4.	Mean analysis of all Hawaiian streams and springs.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Silica	0.0030	0.0076	0.0072	0.0026	0.0023
Iron oxid and alumina	.0015	.0006	.0004	.0006	.0005
Calcium oxid	.0015	.0076	.0043	.0012	.0015
Magnesium oxid	.0020	.0058	.0051	.0015	.0013
Potassium oxid	.0010	.0006	.0008	.0005	.0005
Sodium oxid	.0030	.0094	.0081	.0030	.0033
Chlorin	.0070	.0200	.0178	.0041	.0040
Sulphuric acid	.0002	.0033	.0027	.0012	.0011
Phosphoric acid	.0000	.0002	.0001	.0001	.0001
Total solids	.0260	.0760	.0600	.0190	.0200
Grains per gallon	18.4	53.5	42.4	13.3	13.6

Samples Nos. 2 and 3 were injuriously affected with salt to a slight degree. These samples were from wells at almost sea level and only a short distance back from the tide line. Waters have been analyzed which showed over 300 grains of salt per gallon, thus showing the infiltration of the sea water. The data that have been furnished demonstrates the primary importance of fully testing the qualities of waters drawn from sources near to the sea, and examples could be produced showing the enormous losses that have followed the ignoring of such tests.

DUTY OF WATER.

By the term "duty of water,"[1] as used in this bulletin, is understood the volume of water that is required to mature a given crop in given conditions of soil and climate. That the duty of water can not be a definite factor, the water being in equal demand and rendering the same service in all locations, has been amply indicated by the facts stated in preceding paragraphs. It has been shown that there are locations where the volume of water directly evaporated from the soil is double the amount removed in other locations and under totally different conditions of climatic exposure and action. Further, it was shown that soils themselves vary extremely in their powers to take up and retain moisture, which affords another illustration of the factors that determine the service of applied water in relation to the crop. If a given volume of water is applied to a soil of low absorptive capacity and with a small retentive power, loss occurs by seepage on the one hand and by extreme evaporation on the other, thus causing a large expenditure by the soil and a minimized service rendered to the crop.

[1] For definition of this term as used in the irrigation investigations of this Department, see U. S. Dept. Agr., Office of Experiment Stations Bul. 86, p. 33.

Again, crops may vary between very wide extremes in the volumes of water they consume per unit of substance formed, and consequently in the volumes necessary to bring them to maturity.

IRRIGATION PRACTICE ON THE HAWAIIAN ISLANDS.

The chief crops that are grown by the aid of artificial irrigation in Hawaii are rice and sugar cane.

The lands used for rice are the lowest flats found at the outlets of valleys and close on the sea. Irrigation is practiced upon all these lands, but no means of determining the volume used per acre have been adopted, and data are not at hand bearing on the question.

Sugar production is, relatively speaking, a recent matter so far as the present volume of production is concerned. So late even as 1880 the output is recorded as being 30,000 tons, while the production last year (1899) was 282,807 tons. The part played by artificial irrigation in the production of the Hawaiian crop is seen from the following statement:

	Tons.
Sugar grown by natural rainfall	116, 382
Sugar grown by irrigation	166, 425

The area to which water is artificially applied is yearly increasing, and in two years more than two-thirds of the crop, which is also vastly increasing, will be grown by aid of irrigation.

The richest lands upon the islands are those lying toward and a little above sea level. In most of the districts, however, the rainfall over the low-lying lands, and especially upon the leeward side, is utterly insufficient to produce the sugar crop. Until the practice of irrigation was adopted these lowlands were useless, but now they are, beyond comparison, the richest and most productive.

The primary source of water upon the Hawaiian Islands is rainfall. Two unfavorable conditions attend its precipitation: (1) The maximum quantity falls during the cool season, when the crops are not in a state of maximum growth and able to make use of it, and (2) the chief precipitation is over the mountain areas, where the water falls, soaks down into the rock strata, and runs largely to the sea, unless arrested and returned to the land. An illustration of the variation of rainfall with altitude is afforded by the following table:

Variation of rainfall with elevation.

	Rainfall at sea level.	Rainfall at elevations of 2,000-3,000 feet (2½ miles from sea).
	Inches.	*Inches.*
Honolulu (Oahu)	32	118
Haua (Maui)	28	179

The apparently disadvantageous circumstance of heavy precipitation at maximum elevations has been turned into a special advantage by engineering means. In certain districts the water is collected by small ditches over the mountain areas, where it falls, and is conducted by main ditches or by flumes down to the cane-bearing lands below, over which it is distributed by gravity. Where the rainfall can not be easily collected over the mountain areas, the water which sinks down into deep substrata is tapped and arrested at or near sea level, where it is found running toward the sea. In places where the lava rock strata run out before reaching the sea the water comes to the surface in springs, but the great body flows out or is held in underground reservoirs at varying depths, and has to be sought for by means of wells, from which the water is lifted and forced up to considerable elevations by high-duty pumps, where it is distributed.

The pumps that are in service on the islands are chiefly of American build, and are in some instances of large capacity. Their duties range from the small lifts of the centrifugal pumps to those raising 12,000,000 gallons per 24 hours. (Pls. I and II.)

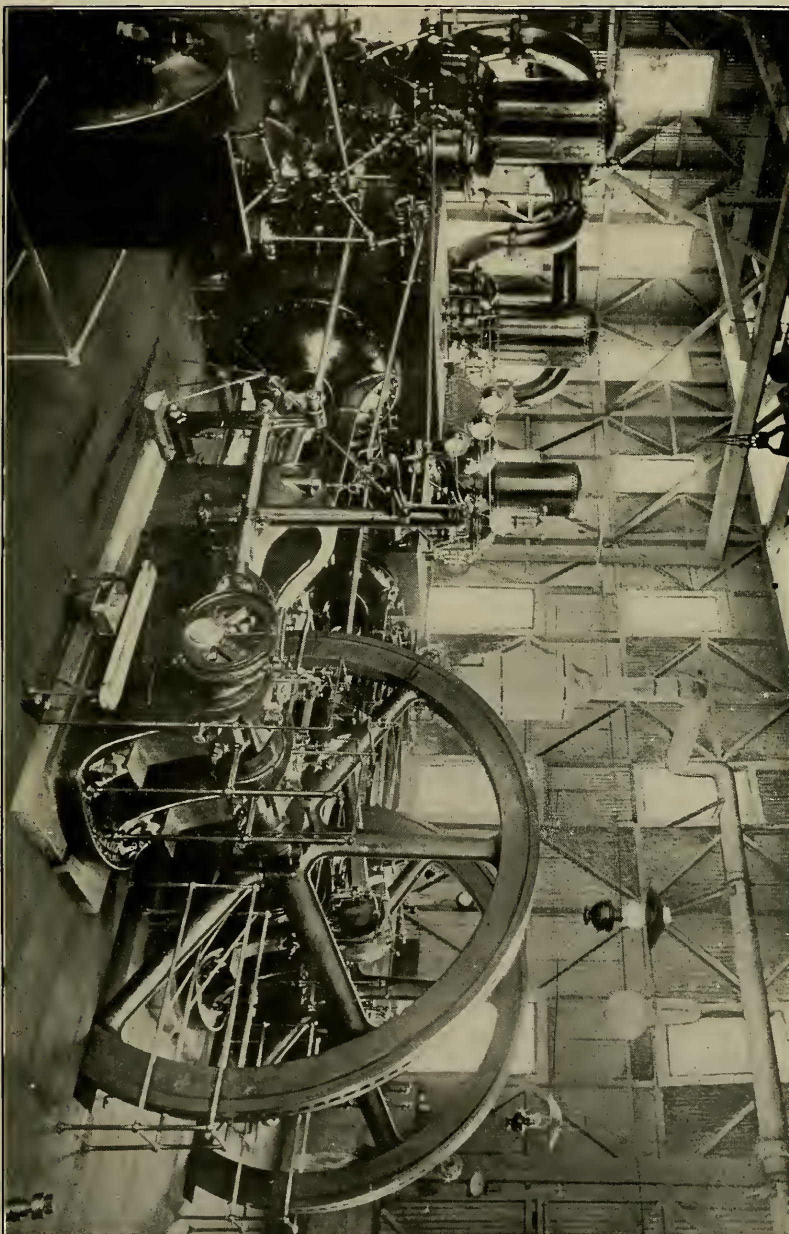
The amount of water applied in the irrigation of Hawaiian sugar cane is controlled mainly by the volume of the supply. Concerning the volume that is considered necessary and that is taken as a basis of estimation in calculating the water required by any given plantation and the capacity of the pumps necessary to lift and apply it, reference is had to the data contained in a report on investigations made in 1889 by Messrs. J. D. Schuyler and G. F. Allardt, civil engineers.[1] The data and the views contained in that report were made the bases of operations by the authorities quoted, and they are still the views and represent the practice of those men who were on plantations at the time of the publication of the report in 1889. Other views and other methods are now coming into practice which are based more largely upon the principles set forth in the earlier paragraphs of this report and upon results obtained in actual experiments in irrigation. These will be spoken of later. The report referred to says:

It seems to be the general practice here [island of Oahu] to irrigate "plant" cane every three or four days for the first month after planting or until it has made a strong growth of root and stalk. After that a watering is given every seven days for a time, diminishing to one watering every ten days, which is continued for about fifteen months from the time of planting, or until the maturity of the cane. It is customary to cease irrigation from one to three months before cutting. If, as in some districts, the cane did not mature short of eighteen to twenty months from time of planting, the period of irrigation would be from fifteen to eighteen months. In making our estimate we have assumed that fifteen months of irrigation would be the average required for sugar cane on the leeward slopes of this island [Oahu]. Three waterings per month is the least that is considered safe to apply to keep the cane growing

[1] "Water supply for irrigation on the Honouluili and Kahuku ranchos," Oakland, Cal., 1889, pp. 32; see also Special Consular Reports on Canals and Irrigation in Foreign Countries, 1891, pp. 395–407.

EXTERIOR VIEW OF A PUMPING STATION IN HAWAII.

The large pipe which conveys the water from the pumps to the fields is shown mounting the side of the gulch in which the station is located.



INTERIOR VIEW OF THE PUMPING STATION SHOWN IN PLATE I.

Two pumps are in use in this station: one lifts 12,000,000 gallons 380 feet every twenty-four hours, the other lifts 10,000,000 gallons 150 feet in the same time.

without check. In localities corresponding in position and climate to Honouluili it is customary to maintain this periodical irrigation regardless of the rainfall. The rain may at times exceed the quantity applied artificially, but irrigation is performed as usual notwithstanding, in order that there shall be no break in the waterings. It seems to be generally understood by all planters that the depth of each watering shall be at least an average of 3 to 4 inches over the whole surface. Where the intervals between waterings are ten days and the depth applied is 4 inches, 1 cubic foot of water per second will perform a duty of 59.5 acres. With intervals of seven days and the same depth of water applied, 1 cubic foot per second would irrigate but 41.6 acres, or 55.5 acres if the depth applied is but 3 inches.

At this place it may be convenient to state, for the use of persons who judge by the standard of rainfall, that 1 cubic foot of water per second is equal to a flow of 294,700,032 United States gallons in fifteen months, and that if this volume were applied to 41.6 acres that would be equal to 7,108,173 gallons per acre, or a rainfall of 210 inches per year and 262 inches to mature the crop.

The report proceeds to give examples, and begins with the Hawaiian Commercial Company's plantation at Spreckelsville, island of Maui, of which it says:

The record for the calendar year 1888 shows that there was delivered to the plantation the following quantity of water:

	Cubic feet.
From the Haiku ditch	1,175,000,000
From the Waihee ditch	919,000,000
Total	2,094,000,000

Or 15,700,000,000 gallons. The rainfall during this period was 19.08 inches.

With this water there were irrigated 2,000 acres of "plant cane" and 600 acres of "ratoons" (volunteer second crop). In addition, 400 acres of seed cane were irrigated once a month, consuming a quantity roughly estimated at 70,000,000 cubic feet. The remaining 2,024,000,000 cubic feet would be equivalent to a constant average flow through the year of 64.18 cubic feet per second, which, divided into 2,600 acres, would appear to give an average duty of 40.5 acres per cubic foot per second, and to indicate that the mean depth applied was nearly 18 feet in the aggregate (22 feet, or 264 inches, for the crop period of fifteen months).

The report states that the explanation for "this seemingly low duty" may be found in the fact that the water was also used for cattle, domestic, and other purposes.

Mr. Hugh Morrison, general manager of the plantation at Spreckelsville, states, as an epitome of his experience, that 11,000 cubic feet per acre applied every seven days will produce the very best results in growing sugar cane. Covering the period of fifteen months already stated, that amount was equal to 5,348,200 gallons per acre, or a rainfall of 197 inches, which with the 19.08 inches of actual rainfall makes a total of 216.08 inches to produce the crop. The report continues:

Mr. Morrison further adds that it is almost impossible to put on too much water (of course within reasonable limits), and that the more water is applied, without going to extremes, the greater the yield. He has obtained a yield as high as 10 tons of sugar per acre in localities sheltered from the wind. The average yield of 1888 on 2,000

acres of plant cane was 5¾ tons of sugar per acre; the ratoon crop averaged 3½ tons per acre. * * *

On the Wailuku plantation, island of Maui, where the water supply is very abundant and in excess of the needs of the plantation, the consumption is equal to a duty of about 50 acres per cubic foot per second on plant cane and 60 acres on ratoons.

On the Hamakuapoko plantation, Maui, where the average annual rainfall is reported as 35.2 inches, the amount applied is stated by the superintendent, Mr. James Cowan, to be 10,890 cubic feet per acre to each watering. The intervals between waterings are seven days, and consequently the duty of water in continuous flow is 55.5 acres per cubic foot per second.

This amount is equal to a depth of 195 inches, which, with the natural fall of 35.2 inches of rain, is equivalent to a total rainfall of 230.2 inches to mature the crop, or 184.2 inches per annum. Continuing, the report says:

In making up these figures, however, Mr. Cowan qualified them by saying that they are for the full capacity of the ditch, which is not always full when required, and is only partially compensated for full flow by the rainfall. * * * The average yield of the plantation is given at 5.6 tons of sugar per acre for plant cane and 4 tons for ratoon crop. * * * He summarizes by stating that to raise 1 pound of sugar requires about 51.8 cubic feet of water.

There are so many elements of uncertainty included within the foregoing statement that it must be considered as merely an approximation to the truth. The report further states:

On the Kekaha plantation, Kauai, water is obtained by pumping to a height of 18 to 36 feet, an average of about 27 feet. The delivery of the water is contracted for at the rate of $35 per acre per annum. The contractor is required to deliver sufficient water to irrigate 700 acres every ten days to an average depth of 4 inches at each watering. The duty thus performed, presuming the quantity contracted for is fully delivered, would be 59½ acres per cubic foot per second. The pumping is done during ten hours each day. The three pumps require to have a capacity of 7,000,000 gallons per day each. Coal costs $14[1] per ton at the pumps. A very unusual yield is reported from this plantation. Ratoon crops for seven consecutive years are said to have produced an average of 5 tons of sugar per acre each year.

In summing up their observations, Messrs. Schuyler and Allardt say that a greater duty than 60 acres per cubic foot per second can not possibly be considered safe; or in other words, at least 5,000,000 gallons per acre are required to make the crop.

The data and conclusions furnished by Schuyler and Allardt have been given at length, for the reason that they formed the basis of computations some ten years ago and are still followed by the older plantation authorities. During the past six months two persons who are connected with the opening up of new plantations assured the writer that those estimates "were not conservative enough to be safe, and that in their calculations and provisions they were providing for not less than 6,000,000 gallons of water per acre for the crop." The more conservative estimates of those gentlemen are not based upon any ascertained knowledge of the requirements of the soil and crop. They are merely the result of a wish to be safe. As a consequence, when

[1] It now costs $10 per ton.

FIG. 1.—ARRANGEMENT FOR IRRIGATING PLATS AT THE HAWAIIAN EXPERIMENT STATION.

FIG. 2.—A SUGAR FACTORY IN HAWAII.

the basis of 6,000,000 gallons per acre for the crop becomes the practice, some other gentlemen of conservative mind who also wish to be safe will appear who will think 7,000,000 gallons a necessary provision. At present the practice upon the plantations is not resting upon ascertained requirements which can be arrived at only by the aid of a knowledge of the physical laws that have been set forth and by actual tests involving the determination of the amount of water that the crop during the different stages of growth requires in given conditions of soil and climate.

STUDY OF IRRIGATION AT THE HAWAIIAN EXPERIMENT STATION.

In view of the absence of established data bearing upon the actual requirement of the sugar cane in the conditions of soil and climate of the Hawaiian Islands, and also on account of the great variations that obtain in the practice of irrigation, the writer determined upon a series of tests which should be carried out along lines of strictly economic purpose, but controlled by the aid of such physical and chemical observations as were previously shown to underlie any system of rational irrigation.

The Hawaiian Experiment Station is located in the suburbs of Honolulu and comprises 5 acres of land. In laying out the area into divisions and plats special provisions was made for the use of irrigation water. The water supply is that of the city municipality, and it is laid on by iron pipes with very numerous faucet discharges. The distribution is made by means of rubber hose, thus controlling the delivery at any place or time. (Pl. III.)

The topography of the field is favorable for irrigation, its surface being relatively level.

The soil is exclusively derived from the decomposition of basaltic lavas. There is a depth of 15 inches of tillable earth resting upon a porous subsoil, an understratum which is composed of chips of lava stone, scoria, and black sand. The total mass of soil is thus relatively small, 1 acre to the depth of 15 inches weighing 4,368,825 pounds. The constituents of the soil are shown in the following table:

Analysis of soils at Hawaiian Experiment Station.

Soil constituents.	Amounts present.	Soil constituents.	Amounts present.
	Per cent.		*Per cent.*
Moisture	9.526	Ferrous oxid	5.515
Combustible matter	9.347	Alumina	12.540
Insoluble silica	15.660	Manganese oxid	.145
Soluble silica	17.058	Lime	.861
Titanic acid (TiO_2)	2.460	Magnesia	.821
Phosphoric acid	1.050	Soda	.175
Sulphuric acid	.164	Potash	.581
Carbonic dioxid	.080	Nitrogen	.149
Chlorin	Trace.		
Ferric oxid	23.630	Total	99.862

The power of this soil to take up water is 48.5 per cent. The climatic conditions have already been amply discussed, since the data contained in the earlier paragraphs of this work bearing upon the evaporation of moisture from water and soil surfaces and the transpiration of water by the sugar cane were all observed and recorded at this station.

By the mode of applying water in use at the experiment station every gallon of water that goes onto each experimental plat is measured and recorded. This exactness is absolutely necessary not only in order to note the action of the water, but also that of other factors upon the development and results of the crop. Consequently the records of rainfall and the measurement of the water applied furnish the total water at the disposal of the crop in the course of its growth.

Two crops of cane have already been grown upon the experiment station grounds by the aid of irrigation. The first crop was planted in July, 1897, and harvested 20 months later. The second crop was planted late in June, 1898, and is now being taken off (March, 1900). The period of irrigation, however, extended from the time of planting until November of the following year, making some 17 months during which water was applied. Unless the weather is extremely dry, the cane does not receive water several weeks previous to its being cut, in order to induce a more thorough ripening. Excess of moisture operates to keep the cane immature and induces new shoots to appear and grow, thus injuring the crop.

In the following table are recorded the amounts of water the crops received during the years specified as rainfall and by irrigation:

Amounts of water received by crops at Hawaiian Experiment Station.

Month.	1897–98.		1898–99.	
	Rainfall.	Irrigation.	Rainfall.	Irrigation.
	Inches.	*Inches.*	*Inches.*	*Inches.*
July	0.63	3.0	0.94	4.0
August	1.02	3.0	1.58	4.0
September	4.12	1.5	.88	4.0
October	2.07	3.5	1.75	3.0
November	2.11	2.0	1.32	3.0
December	.88	3.5	1.86	2.0
January	6.18	0.0	1.00	4.0
February	8.04	1.0	3.75	1.5
March	10.39	0.0	3.98	3.0
April	1.21	1.0	.85	4.0
May	.84	4.5	2.01	4.0
June	2.60	2.0	.88	7.0
July	.94	5.0	.17	7.0
August	1.58	5.5	1.90	9.0
September	.88	6.5	.75	8.0
October	1.75	4.5	2.92	6.0
November	1.32	1.0	.47	3.0
Total	46.56	48.0	26.01	76.5

From the data in the rainfall columns it is seen that the most of the rain falls during the cooler months of the year, which are the months of minimum plant growth. This is a special climatic drawback. The

IRRIGATED AND UNIRRIGATED SUGAR CANE AT THE HAWAIIAN EXPERIMENT STATION.

most advantageous combination of climatic conditions is the concurrence of high temperature and maximum rainfall, or a moist, hot season, and a dry, cool season, which combination occurs in the sugar zone of Queensland. It is very apparent that water does not possess a maximum value if it falls during the cool season and when the crop is not in full growth and able to make use of it. For this reason a less value and importance have to be ascribed to the rainfall of these islands than might otherwise be.

The table shows that, during the years 1898 and 1899, the rainfall covering the period of seventeen months was only 26.01 inches, or 18.3 inches per annum. It should also be understood that the extra deficiency in the rainfall can not be measured by the simple amount of that deficiency, for the reason that, instead of the cloudy, wet days when the rain should have fallen, dry days of high evaporation occurred, thus aggravating the natural situation and causing a greater need for the water supplied by artificial means. When the totals of the data contained in the table are brought together, it is seen, however, that the differences in the total amounts of water consumed by the respective crops are not material and no greater than has been reasonably accounted for.

Total water received by two crops of sugar cane.

Crop period.	Rainfall.	Irrigation.	Total.
	Inches.	*Inches.*	*Inches.*
1897–98	46.56	48	94.56
1898–99	26.01	77	103.01

Before proceeding to furnish the full results of the two crops attention may be called to the comparative value of the water which fell as rainfall and that of the water applied in irrigation, taking the sugar equivalent as the expression of value. It is possible to do this by the use of data obtained during the season 1897–98, when tests were carried out in the experiment field under identical conditions of soil, cultivation, and fertilization. In these tests twenty plats of cane were grown by the aid of irrigation in addition to the rainfall, and eight tests were made without any irrigation (Pl. IV), the results being as follows:

Yield of irrigated and unirrigated cane.

Number of tests.	Rainfall.	Irrigation.	Yield of sugar per acre.
	Inches.	*Inches.*	*Pounds.*
20	46.56	48	24,755
8	46.56		1,600
Difference in favor of irrigation			23,155

Nothing could show more conclusively than these figures the necessity of irrigation under the existing conditions, and the enormous sugar-equivalent value of irrigation water applied systematically to the cane during the season of maximum growth, which is the summer season. An equal volume of water falling in heavy rains during the cool season, when growth is slow, is largely lost through percolation and produces a comparatively small value in sugar.

The following tables contain a statement of the crops of 1897–98 and 1898–99 and of the value of the water applied by irrigation. A brief table is first given showing the average weight of cane and yields of sugar for the two seasons:

Yield of cane and sugar at Hawaiian Experiment Station.

Crop period.	Number of tests.	Yield of cane per acre.	Yield of sugar per acre.
		Pounds.	*Pounds.*
1897–98	20	166,562	24,755
1898–99	15	192,440	27,133

These are the results in cane and sugar per acre of crops that were about nineteen months on the ground and subject to systematic irrigation for seventeen months.

The relation of the crops to the total volume of water received both as rainfall and by irrigation is as follows:

Water required to produce 1 pound of sugar.

Crop period.	Rainfall.	Irrigation.	Water per acre.	Yield of sugar per acre.	Water required to produce 1 pound of sugar.
	Inches.	*Inches.*	*Gallons.*	*Pounds.*	*Pounds.*
1897–98	46.56	48	2,567,682	24,755	865
1898–99	26.01	77	2,797,133	27,133	859

The volumes of water consumed by the cane per pound of sugar made during the growth of the two crops are very nearly the same. During the growth of the crop of 1897–98 some of the rainfall occurred in heavy precipitations, and it was ascertained that water escaped through the subsoil and was lost. During the production of the crop of 1898–99 none of the water received, either from rainfall or from irrigation, was lost in this manner. No single rainfall exceeded 1 inch, and in irrigating no more than 1 inch of water was applied at any single watering.

It is seen from the preceding tables that the maximum quantity of water applied artificially during a season of extreme drought was 77 inches during a period of seventeen months, or 2,090,858 gallons of water per acre, to make a crop containing 27,133 pounds of pure sugar per acre. These results are the average of fifteen tests, which were made under identical conditions of soil, cultivation, and fertilization.

The following table brings together the estimates of the duty of water in the Hawaiian Islands contained in the report of Schuyler and Allardt,[1] previously referred to, and the results of experiments made at the Hawaiian Experiment Station by the writer:

Duty of water in Hawaiian Islands.

	Water applied per acre per crop.		Yield of sugar per acre.	Water required to produce 1 pound of sugar.
	Depth.	Quantity.		
According to Schuyler and Allardt:	*Inches.*	*Gallons.*	*Pounds.*	*Pounds.*
Spreckelsville (1)	262.00	7,114,348	11,100	5,345
Spreckelsville (2)	216.00	5,865,264	11,100	4,407
Hamakuapoko	230.20	6,250,850	11,300	4,613
Kekaha	198.20	5,381,428	12,000	3,740
At the experiment station:				
First crop (1897–98)	94.56	2,567,682	24,755	865
Second crop (1898–99)	103.01	2,797,133	27,133	859

In the above table the yields of sugar per acre as given are higher than stated by the plantation authorities. For Spreckelsville the yields as stated were "for plant cane, 5.75 tons of sugar per acre; the ratoon crop, 3½ tons per acre;" for Hamakuapoko, "5.6 tons of sugar per acre for plant cane and 4 tons for ratoon crops," and for ratoon crops at Kekaha "5 tons of sugar per acre for seven years." These figures express the amounts of sugar per acre obtained by the mills and marketed, and not the full amounts produced by the soil. As a correction, and to make the figures comparable with the statement of experiment-station yields, 20 per cent has been added to the amounts given by the plantations. This may be rather too much, but it has to be remembered that the mills ten years ago did not obtain as much sugar from the cane as they do to-day. However, the figures of yield as given are probably a little in favor of the plantations.

In comparing the data contained in the table it is again to be remembered that the figures furnished by the plantations state what was actually being done by those plantations. The experiment-station data show what has been done and what it is possible to do, where the irrigation is carried out according to scientific principles and where the conditions are under control. Upon a large plantation the conditions can not be controlled to the same extent as is possible with experiments on limited. areas. This in no wise lessens the force of the fact that plantations are wasting huge volumes of water in their practice of irrigation or removes the necessity of examining into and determining the location and causes of the waste.

The figures contained in the last column of the table show the pounds of water received from rainfall and irrigation per pound of sugar grown. Instead of using sugar as the standard we may use the total

[1] Special Consular Reports on Canals and Irrigation in Foreign Countries, 1891, pp. 396–398.

dry substance of the crops in its relation to the water received per acre. The exact data furnished by the station's experiments enable this to be done:

Water used to produce 1 pound of dry substance.

Crop period.	Water received per acre.	Dry substance produced per acre.[1]	Water required to produce 1 pound of dry substance.
	Pounds.	*Pounds.*	*Pounds.*
1897–98	21,414,457	98,725	216
1898–99	23,328,089	110,087	212

[1] By "dry substance produced per acre" is meant the total amounts of water-free cane and leaves produced by 1 acre of ground. During the crop period 1897–98 some rainfall water was lost by percolation through the subsoil, but how much was not ascertained. During the growth of the crop of 1898–99 no water was lost. Two hundred and twelve pounds of water were used, therefore, to produce a pound of dry substance.

The most fertile plantation upon the Hawaiian Islands last year yielded 20,500 pounds of sugar per acre, and, according to the estimate of the manager, consumed a little over 5,000,000 gallons of water per acre. On this plantation a less volume of water produced double the quantity of sugar that was obtained at Spreckelsville and Hamakuapoko; consequently the waste of water at those places must have been great. Upon this fertile plantation, however, there are ample evidences of past excessive irrigation and waste. The volume of water used per acre was double that used at the experiment station to produce less sugar per acre.

A small crop of say 30 tons of cane or 4 tons of sugar per acre can not in its growth consume the volume of water demanded by a crop of 80 tons of cane or 10 tons of sugar per acre. It can consume only a fixed portion of that volume. The same principle applies in the demands made upon the soil for plant food. The large crop absorbs more of the soil constituents to compose its substance and promote its growth. Water is only one of the essential factors which control the size of the cane or other crop. The depth and fertility of the soil, the fertilizing elements supplied, and the extent of cultivation are all potent factors affecting production. It has already been shown in a previous paragraph that the growth of the cane and the amount of water used during increased growth, as indicated by the increased transpiration of water by the cane, are very noticeably influenced by the action of nitrogenous fertilizers.

DISTRIBUTION OF WATER.

In the Hawaiian Islands sugar cane is irrigated exclusively by means of ditches and furrows. In laying out a field to be planted in sugar cane the first step is to make a survey of the area and to determine its contour. The notes of the survey will show the direction in which the cane furrows shall be constructed and also show where the laterals

which feed the furrows should be located. On uneven ground the furrows are curved in order that the grade may be kept uniform.

If a field is practically level—and there are vast areas of relatively level land in locations where cane sugar is likely to be grown—the furrows are dug straight through the field. The most level field, however, usually has a dominant decline in some direction which is usually determined by the general formation of the lands of the region. The Hawaiian Islands are of volcanic origin, and hence the general slope of the land is from the craters to the sea. The country is mountainous in the neighborhood of the volcanoes. The slopes become flatter as lower levels are reached, until the decline apparently disappears in the lands bordering on the seacoast. The

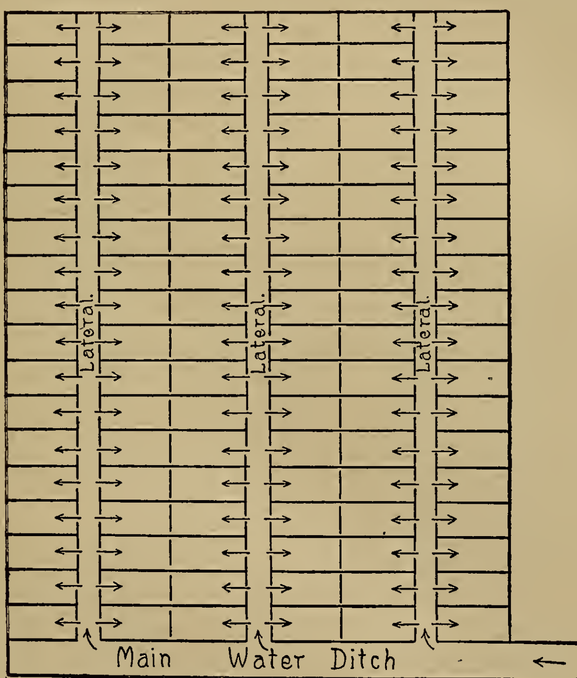


Fig. 2.—Irrigation of sugar cane on level land by means of laterals.

latter have been deposited by streams running from higher lands. In spite of the flat appearance of these lowlands they generally have a decline toward the sea which is not only sufficient to make the distribution of water a simple matter, but also to effect the discharge of underground water. This, however, is not always the case, the writer having several tracts in mind where the ground water can not find a discharge owing to its surface being but slightly above the level of high tide.

The diagram (fig. 2) shows a field that is furrowed for planting and has subditches dug for the distribution of water. The furrows are made at right angles to the fall of the land and the distributing

laterals are constructed at right angles to the furrows, or parallel with the natural water flow.

As the diagram shows, the main ditch feeds the laterals and these feed the furrows. The laterals discharge into the furrows on each side, the water flowing one-half of the distance between laterals in each direction. The furrows in the diagram are between the rows of cane. In the Hawaiian Islands the cane is generally planted and kept in furrows and not ridged up, and the water is applied in those furrows, running in and out around the cane stalks. In other countries visited by the writer, where irrigation is required during a part of the growing season, the cane is more generally upon the ridge and the water is applied between the rows of the cane, as shown by the diagram. The practice is controlled by such factors as the nature of the soil, the rainfall at specific seasons, and the related questions of drainage.

In the diagram (fig. 2), the lines indicating the rows of cane are assumed to be 5 feet apart, which is the usual distance. In some situations, owing to local causes, the distance between the cane rows may be as much as 6 feet or as little as 4½ feet. The distance between the laterals is assumed to be 30 feet, which means that the water is intended to flow only 15 feet from each side of the laterals that are feeding the furrows. The lines running midway between but parallel with the laterals represent earth dams in the furrows. These limit the length of flow of the water from the laterals on each side. Only lands having a very even surface can be laid out upon the simple plan of the diagram.

Before speaking in detail of the methods of applying water, one other system will be described. This provides for the direct discharge of the water from the main ditch into the furrows. The system (fig. 3) has been observed by the writer, its results considered, and it is mentioned chiefly to show its essential defects.

In the system illustrated in this diagram (fig. 3), the water supply is from a main ditch of considerable size (a width of 5 to 8 feet has been observed), which feeds the water furrows between the rows of cane direct, as illustrated by the arrows in the diagram. The cane rows are drawn straight through the field. The water flows parallel with the rows of cane and not at right angles to them, as shown in diagram (fig. 2). Consequently the water has to distribute itself by flowing from the main ditch to the opposite end of the field. As already remarked, this system of distribution is exemplified in order to make clear its very palpable drawbacks, which will be briefly explained.

Volume of the application.—Schuyler and Allardt, in treating of this subject under the conditions of the Hawaiian Islands, state that "it seems to be generally understood by all planters that the depth of each watering, i. e., the volume of each application, shall be at the least an average of 3 to 4 inches over the whole surface of the ground." The same authors quote one of their witnesses as saying

"11,000 cubic feet per acre every seven days will produce the very best results in growing sugar cane." That volume is equal to 3½ inches of water over the whole ground per weekly application. Another example from the same authority gives "10,890 cubic feet per acre to each watering every seven days." This volume is equal to an application of 3 inches of water over the whole ground once a week. When the small rainfall was added to the amounts applied by irrigation upon the plantations spoken of by Schuyler and Allardt,

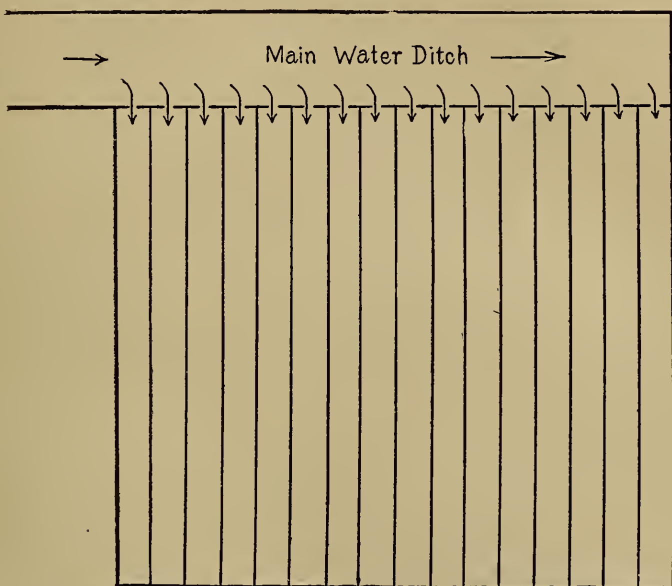


Fig. 3.—Irrigation of sugar cane on level land by direct discharge of the water from the main ditch into the furrows.

then the average application per seven days over the stated period of fifteen months or sixty-five weeks appeared as follows:

Depth of water applied to sugar cane during sixty-five weeks (rainfall and irrigation).

Plantation.	Water applied per acre.	Mean application per week.
	Inches.	*Inches.*
Sprecklesville (1)	262.0	4.03
Sprecklesville (2)	216.0	3.32
Hamakuapoko	230.2	3.54
Kekaha	198.2	3.05

The figures in the outer column indicate the average depth of application per week during the growth of the crop, which is given as sixty-five weeks. Concerning the value placed upon the rainfall, Schuyler and Allardt say, "the rain may at times exceed the quantity

applied artificially, but irrigation is performed the same as usual, notwithstanding, in order that there shall be no break in the continuity of the waterings."

Mode of application.—The two chief systems of applying irrigation water have already been spoken of: First, by flooding, and second, by furrow application (Pl. V). Two methods of applying water by the system of furrows have also been considered and illustrated (figs. 2 and 3). For the present purpose we return to the method exemplified by fig. 2, or the system of a main ditch which feeds the laterals which in turn feed the furrows, the furrows being laid out at right angles to the laterals, which are drawn parallel with the natural slope of the land or with the water flow. As represented by fig. 2, the section of furrow between the laterals is assumed to be 30 feet in length, each lateral watering 15 feet on either side. This illustration is intended to exhibit an example of water distribution in the furrow that is highly efficient from the standpoint of utilization of the water. Upon many plantations, however, the method of feeding the furrows from both sides of the laterals is not in practice. Very frequently the water is let into the furrows from only one side of the laterals, although this practice is giving way. Again, the length of the section of furrow along which the water has to flow, in present practice, varies from 30 to 50 feet, sections 35 to 45 feet being the more common.

The length of time that a given flow of water will require to reach the end of a furrow section, all other things being the same, will be in proportion to the length of the section; consequently, the length of time that the water must flow over the end of the section of furrow abutting the feeding lateral is decided by the time that the water requires to reach the farther end of the furrow. The other factors also controlling the length of time required to reach the whole length of the furrow are the volume of the stream, the slope of the ground, and porousness of the soil. When the soil is loose, as it is in furrows newly made, the water travels slowly, it being absorbed by the soil at the end of the furrow next to the inlet. The continued flow finally saturates the soil, and the water gradually travels along the furrow until it reaches the farther end, when, after a short time, it is shut off and turned into the next furrow. As the soil in the furrow becomes more solid and close with time the water travels more quickly, and the distribution tends to become somewhat more even, but in such a length of furrow the distribution never becomes uniform. The economic results of this uneven distribution are immediate, and as follows: The effect of an excess of water at the end of the furrow next to the inlet upon the cane is first to retard the germination of the seed by largely excluding the air from the soil, without which incipient growth can not proceed. The effect upon the cane continues and has been observed even up to its maturity. The action upon the soil is first seen in the

IRRIGATING SUGAR CANE SEED IN HAWAII.

washing out of the soluble constituents upon which the crop depends for its nutrition. If the action is continued in lowlands where there is imperfect drainage, the mechanical state of the subsoil is seriously affected, becoming close and more impervious, which is due not only to the water but also to the carrying down of soluble alkaline salts. While these effects are taking place at the end of the furrow which receives the great excess of water, the 15 feet at the farther end is not receiving moisture enough for the requirements of the cane; the cane there is suffering for want of water, and the 15 feet next to the inlet is suffering from an excess of water. The middle 15 feet in the section is the only portion which is receiving approximately an average of the quantity that is being applied. Were the sections of furrows only 15 feet long, with laterals feeding the furrows on each side, the distribution of the water would be relatively even over the whole surface of the ground.

At the Hawaiian Experiment Station the land is relatively level. The furrows are parallel and are 5 feet apart. They are also divided into sections 10 feet in length for irrigation. At the first irrigation and afterwards, until the cane becomes too large for their use, the sections are divided by iron gates that are made to fit and block the furrow. Later, permanent divisions of earth are made. Each section of 10 feet receives, by actual measurement, its quota of water, the number of gallons applied meaning either half an inch, 1 inch, or whatever is determined upon. By this system the ground receives uniformly the same depth of water.

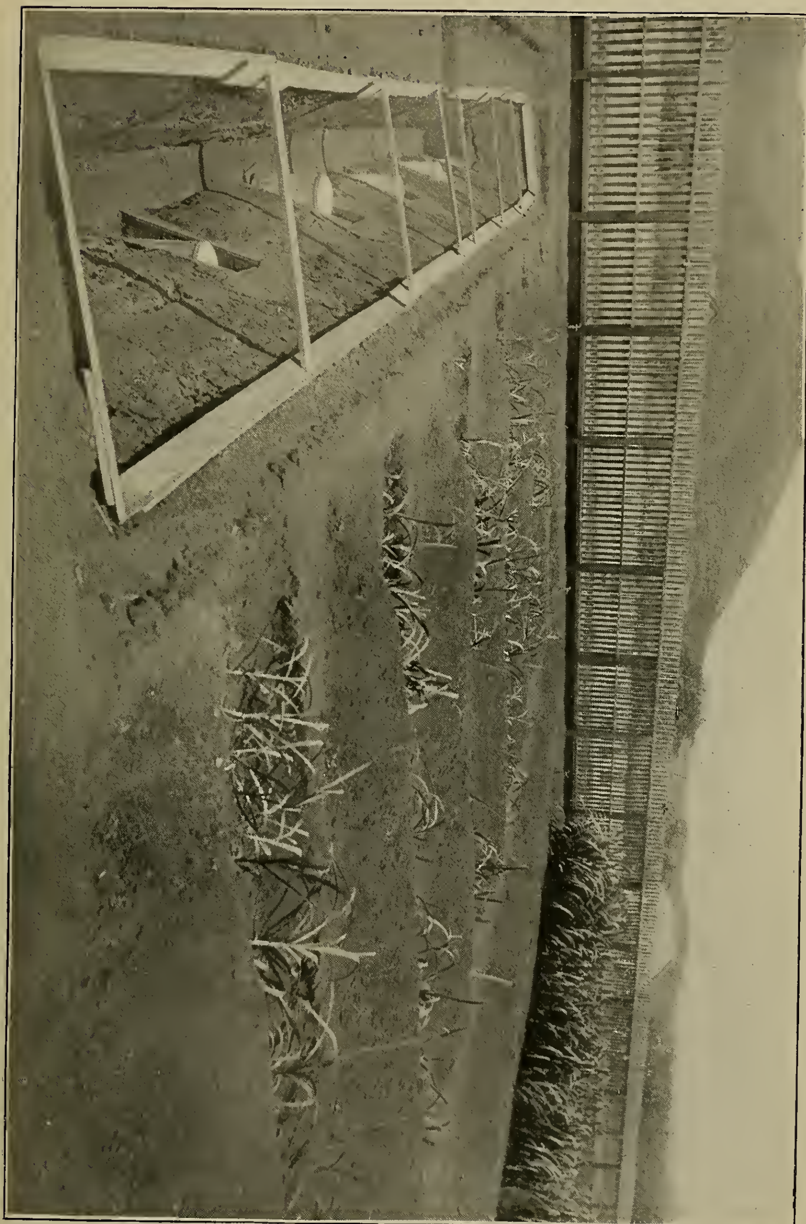
Returning briefly to diagram (fig. 2, p. 29), it can now be better indicated what the results are when this system is adopted. As will be remembered, the water is supplied directly by a main ditch. From it each furrow is fed, the water being let in and the flow continued until it reaches the farther end of the field, which in some cases is from 400 to 600 yards distant. After the remarks already made upon the impossibility of an even distribution of water by furrows that are only 35 to 50 feet long, it is not necessary to consider in detail the results of pouring water into furrows until it traverses a length of 500 yards. If the soil is porous, one-half of the field is soaked to ruin, while the farther half receives only half the water it could use. If the subsoil is close and impervious and the volume of water applied is near the average needed for uniform irrigation of the cane, the excess travels to the farther end of the field, where it stands and becomes stagnant.

Frequency and volume of application.—The volume of water to be applied and the frequency of the application are controlled by the crops being grown and the system of irrigation in use. The volume of water applied and the manner of applying it are factors which in one respect control the frequency of the application. If the sections of the furrows exceed a given length, say 15 feet, it will be impossible

to apply a small volume, since the water would not reach the farther end of the furrow. If, however, we adopt a length of furrow not exceeding 15 feet, we then make it possible to lessen the volume of the application and yet secure good results by a more frequent application of the reduced volume.

In considering the question of the volume of water that can be applied without loss, we are led back to a former paragraph where data are given upon the relative power of soils to absorb and retain moisture. These physical properties, however, are not the only factors which determine the volume of water that an acre of land can hold and the volume of water that may be applied. The mass or depth of the soil is a still more significant factor. Deep soils, such as exist on these islands, where the depth may be 5 or more feet, can take up a large volume of water. Of course, if a large volume is repeated often enough and at short intervals, even such a soil will become saturated, and then the water will escape and be wasted. There are soils, however, and over considerable areas of the Hawaiian Islands, which are relatively very thin, the depth varying from, say, 8 to 15 inches. It is at once apparent that such soils, even if their absorptive power is up to the average, can not take up the same volume of water as the deeper soils spoken of, so that the escape and waste of water from them is not only great but much more rapid. Moreover, when a shallow soil, we will say of 12 inches over the level, is furrowed out for planting and irrigation, the depth of soil remaining at the bottoms of the furrows is reduced to about 6 inches. When the water is run into the bottom of the furrow it has merely 6 inches of soil to absorb it and prevent its escape. The soil of the ridges between the furrows, of course, could take care of the water if the latter were being spread over the surface of the whole ground, which is the case under natural rainfall. It has been observed, however, that the lateral absorption of the water by the ridges is relatively small compared with the vertical rate of absorption of the soil in the furrow bottom, to which force has to be added the action of gravity in drawing the water down.

The volume of water that can be applied by irrigation without loss in Hawaiian soils has not been even approximately ascertained. In 1897 certain tests were made at the Hawaiian Experiment Station in order to obtain some light on this question. These tests were carried out my means of a lysimeter devised by the writer (Pl. VI), which may be briefly described as follows: The lysimeter consists of drains 44 inches deep with galvanized-iron gutters which discharge into a deep trench. At the end of each drain is a receiver that catches any water which is in excess of what the soil can hold, and which consequently passes out through the drains. The soil that was removed for laying in the drains was put back and the drains were completed six months before the cane was to be planted, in order to restore the soil to its normal state. Six such drains were made as described, and cane was



LYSIMETER USED AT THE HAWAIIAN EXPERIMENT STATION.

planted upon five of these, the drains being 8 feet apart and 20 feet long. The nature of the soil has been stated by the analysis in an early paragraph, and the depth is 15 inches, resting upon a porous and rather general subsoil. The depth of the drains was made 44 inches, by which it is seen that some 30 inches of subsoil were cut through. Any water escaping through the soil and through the noncapillary subsoil to that depth it was safely assumed would be finally lost.

When the cane was planted an equal quantity of water, but merely enough to start and keep the cane growing, was applied to each drain or row, this being continued until the cane was 1 foot high, when the actual tests began.

The applications of water to five of the six drains were as follows, drain No. 1 being omitted:

No. 2. Volume equal to one-half inch per week over the whole ground; application made every seven days.

No. 3. Volume equal to 1 inch per week over the whole ground; application made every seven days.

No. 4. Volume same as in No. 3; application 1.5 inches every ten days.

No. 5. Volume same as in No. 4; application 2 inches every fourteen days.

No. 6. Volume and application same as in No. 5.

In No. 6 no cane was planted.

The tests covered twelve weeks, and the results from the drains were as follows:

Water applied to drains, and the quantity lost.

No. of drain.	Total water applied.	Amount and frequency of application.	Total loss from drains.
	Gallons.		*Gallons.*
No. 2	408	$\frac{1}{2}$ inch per 7 days	0
No. 3	816	1 inch per 7 days	0
No. 4	816	$1\frac{1}{2}$ inches per 10 days	32.3
No. 5	816	2 inches per 14 days	131.3
No. 6	816	.....do	272.3

Drain No. 6 was a check, by which is meant that while it was constructed precisely as the other drains no cane was planted upon it, in order to show by comparison the actual work of the cane in preventing the loss of water. As the table shows, Nos. 5 and 6 were watered exactly the same. They received an application every fourteen days and a volume equal to 2 inches over the whole ground. No. 6 drain discharged 272.3 gallons, while No. 5 lost only 131.3 gallons, the difference of 141 gallons being due to the retaining action of the growing cane. Bearing upon this matter of the water-holding action of the cane, it may be stated that drain No. 4, which received 1.5 inches of water every ten days, lost the whole 32.3 gallons of the first and second applications when the cane was still very young. After that period

the more-developed cane took care of all the water applied, none being lost. The same action was observed with drain No. 5, which also lost the most of the 131.3 gallons by drainage during the first three or four applications. These demonstrations of the increasing consumption of water by the crop with its increase of growth are in line with the determinations made with the cane grown in the tub. (See p. 10.)

The results of the lysimeter tests are most valuable and to a degree very conclusive, but an objection may be raised to their complete conclusiveness, due to the circumstance that the conditions were not those of normal, undrained land. The digging of the drains and the putting back of the soil disturbed the natural state of the soil, rendering its condition different possibly from the field as a whole. In view of such possible objections to the results from the lysimeter, two more series of tests were begun, which are not yet fully concluded. The first series was conducted with plats of land one-twentieth of an acre in size, along which three rows of cane were planted. In these there was no disturbance of the soil whatever, no drains being made. At the end of the plats and opposite the middle cane row on each plat an observation hole was dug to a depth of 50 inches. From this hole an iron pipe was driven in a length of 7 feet, 3 feet of the pipe reaching along under the cane row at the said depth of 50 inches. This arrangement was made in order to note the results of applying at regular intervals different volumes of water. The results were as follows:

Water applied to cane crops, and the quantity lost.

Plat.	Depth of application per week.	Volume applied per acre per week.	Water lost.
	Inches.	*Gallons.*	
No. 1	1	27,154	None.
No. 2	2	54,308	Considerable.
No. 3	3	81,462	Enormous.

It was not possible to determine directly the actual loss of water that took place, due to the fact that it sank down into the subsoil over a wide area and did not converge to any point of outlet. The pipes that were driven in discharged some water, but only a small proportion of what was being lost. This was proven by tunneling in to a depth of 1 foot under the pipes, a hole being made some 8 feet long and large enough for a man to creep up. After each irrigation water was found running down into the subsoil and draining out to lower levels. As a considerable discharge was taking place where 2 inches per week were being applied, even when the cane was 6 feet high, an idea is conveyed of the enormous waste that followed the application of 3 inches per week.

The second of this series of tests is still being carried on upon 3 plats of land near by the location of the first series. In this second

series the plan was made the same as in the tests with the lysimeter, a given volume of water being applied to each of the three plats, but with different intervals of time between the applications, as follows:

Water applied to cane in second test.

Plat.	Depth of application.	Volume applied per acre.
		Gallons.
No. 22	1 inch per 7 days	27,154 every 7 days.
No. 24	2 inches per 14 days	54,308 every 14 days.
No. 26	3 inches per 21 days	81,462 every 21 days.

These tests are being made under such conditions as prevail on a large scale upon plantations. In plat 22, which receives its water in weekly applications, the cane seed germinated three days earlier than where the heavier applications were made. On plat 26 the cane came up, not only slowly, but unevenly and with a yellow, sickly color. From the first and up to the time when the cane was nine months old the results of the weekly application were highly satisfactory. As was shown in the first of this series of tests, where a large application of water is made at one time the soil can not contain the whole of it, and a large portion drains into the subsoil and is lost.

A very clear distinction has to be made between a rainfall of 3 inches in depth, which falls during several hours and uniformly over the whole surface of the ground, and an irrigation equal to 3 inches in depth over the whole ground, which is not only applied in bulk within a few minutes, but the application of which is in a furrow comprising less than one-half of the total surface. In the latter case the physical property of the soil—i. e., its absorbent power—has comparatively no time to act and take up the water which is drawn down from the furrow bottom by gravity and out of reach of the cane roots. On the other hand, the rain is distributed equally over the whole ground surface and ordinarily falls at such a rate that the soil particles can take up and hold it. Rainfall, of course, when the ground becomes saturated, behaves like irrigation water, and the excess seeps out below and runs away. In illustration of the different ways in which rainfall water and irrigation water behave, by reason of the different modes of application, and of the phenomena which control these different behaviors, we give some data in detail from our experiment station records (lysimeter tests):

Comparative loss of water received from irrigation and from rainfall, drain No. 5.

Date.	Depth and source of water received.		Height of cane.	Lost from drain.
	Inches.	*Gallons.*	*Feet.*	*Gallons.*
September 15	2, irrigation	136	1	20.50
September 19	$2\frac{1}{3}$, rainfall	158	$1\frac{1}{4}$	86.50
October 12	2, irrigation	136	$3\frac{1}{4}$	27.50
October 27	do	136	5	18.59
October 28	$\frac{1}{2}$, rainfall	34	5	8.25

Before discussing the data in the above table I shall give another table made up of the data attaching to No. 6 drain of the lysimeter:

Comparative loss of water received from irrigation and from rainfall, drain No. 6.

Date.	Depth and source of water received.		Lost from drain.
	Inches.	*Gallons.*	*Gallons.*
September 15	2, irrigation	136	25.5
September 19	2⅓, rainfall	158	91.5
October 12	2, irrigation	136	44.5
October 27	do	136	36.5
October 28	½, rainfall	34	1.0

If we compare the behaviors of drains Nos. 5 and 6 on the dates September 15 and 19, it is seen that No. 5 drain discharged considerably less water than No. 6. At that period there was enough of a root system developed in the cane to enable it to consume the water and to prevent its loss as compared with drain No. 6, where no cane was planted. On October 12 the water consumed by the cane, which was notably larger, was evidently still greater, since No. 5 drain let only 27.5 gallons of water run out, against 44.5 gallons discharged by No. 6. On October 27 the water lost by No. 5 drain is just one-half of the volume given out by No. 6, while on September 15 No. 5 held back only one-fifth more water than No. 6, which was due to the small size of the cane on No. 5 at the earlier date. The next day, October 28, one-half inch of rain fell. Of course the soils of both drains Nos. 5 and 6 were almost at the point of saturation. But it is seen what occurred: No. 5 lost 8 gallons out of the 34 gallons received, while No. 6 drain discharged merely 1 gallon. The result is reversed as compared with what took place on the dates September 15 and 19. In the first place we see the action of even the young cane in largely preventing the loss of water from the drains. When the cane is small its root system enables the soil of No. 5 to hold more of the rainfall water than was held back by No. 6. On October 28, however, the cane was much larger, its leaves almost spread from row to row, covering all the ground, and when even the small rainfall of half an inch fell the largely developed leaves of the cane gathered up the rain and conducted it directly to the cane roots in the furrow, where it sank down and out of the drains. The same amount of rain, but which fell evenly over the whole surface of row No. 6, was taken up more gradually by the soil and only 1 gallon of water discharged at the drain.

The general conclusions to which the observations in detail have led may be expressed as follows:

(1) A greater loss of water results from the application of a given volume by irrigation than occurs when the same volume is received as rainfall. The exceptions to this rule are few, and are confined to examples of crops such as the sugar cane, having a large leaf surface, and which are planted in furrows.

(2) The application of a given volume of water per acre in furrows results in a greater loss and waste than where the same volume is applied by flooding the whole surface of the ground.

(3) A greater loss of water from seepage takes place when a given volume is applied in large quantities at long intervals than when the same volume is applied in small quantities and frequently.

SOME RESULTS OF OVERIRRIGATION.

Effect on the soil.—From the foregoing considerations it is seen that soils can absorb and crops consume only so much water, and that when the applications are in excess of the requirements the surplus must sink into the substrata and be lost. The loss, however, is not covered by the mere waste of the water and the expenditures in getting it onto the ground; a further loss is caused by the action of the escaping water upon the soil and its constituents. Every gallon of water applied in excess of what the soil and crop can retain and use soaks away and is lost. In draining through the soil it dissolves and carries with it much of those bodies that are soluble in water, and as they are the constituents that the plant depends upon for its food, the excess of water acts as a plunderer and depleter of the elements of fertility of the soil. For these reasons the great damage that follows from excessive overirrigation can not be too strongly dwelt upon nor the practice too emphatically condemned. The more permanent injurious effects of the excessive application of water to soils and crops do not become apparent until the damage is done. Certain effects upon the young crop are soon visible and appear in the yellow color and stagnation of growth. The field manager, however, who knows nothing of the physical and chemical properties of soils, of the relative requirements of water by different crops and at the different stages of their development, does not conceive what is happening to the fertilizing elements applied for the use of the present crop and to the natural constituents of the soil upon which future crops must depend. That ignorance in this particular is costly is confirmed by much evidence from the owners of ruined land.

The city of Honolulu is deluged by irrigation, which is not only impairing the sanitary conditions immediately around the dwellings, but is also leading to the formation of fresh water swamps, which in their turn are vitiating the general atmosphere of the place.

In irrigating alkaline lands, the conditions and rules which must be observed differ from those which control the economic irrigation of sweet soils by sweet waters. If no more water is applied than the soil can hold and the crop can make use of, conditions highly unfavorable to plant life can be brought about. The water that is applied in descending in the soil, dissolves and holds in solution a large amount of the salts, and as the water returns to the surface in answer to the calls of evaporation and plant needs the salts are brought

up also and deposited in great excess in the upper stratum or on the surface of the soil. The same result can follow the application of salt waters to sweet soils, of which the writer has noted acute examples upon the Hawaiian Islands. The application of brackish waters or waters charged with chlorid of sodium, magnesium, and lime, even to soils free from deleterious salts, can result in such an accumulation of those bodies in the upper soil that our domestic plants will not grow. The only provision against trouble from the use of saline waters is to use enough to leach the soils and prevent accumulations. To do this perfect underdrainage is essential, and it is further essential to immediately restore to the soil the soluble elements of plant food that have been carried out by the water, along with the injurious salts, or the soil will presently become washed out and sterile. Irrigation of salt or alkaline soils with saline waters is a special matter and demands special treatment, and its requirements must not be confused or mixed up with the factors that exist in normal situations which govern the irrigation of sweet soils with sweet waters.

Upon the island of Hawaii, which is the largest island in the Hawaiian group, there are several well-defined districts which are distinguished by varying climatic conditions. In the district toward the north the average annual rainfall is some 52 inches; in the middle district the precipitation ranges some 25 inches greater; while in the wet district of Hilo the yearly rainfall is some 180 inches, or nearly 15 feet. Upon the other islands of the group similar variations in rainfall are found, but these variations differ not only with the districts but also with the elevation of the land in the same location. Two examples may be cited of extreme variations in rainfall in the same district due to a difference in altitude. In the one, the rainfall at sea level was 30 inches, while at an altitude of 900 feet it was 118 inches per year, and in the other it was 28 inches at the sea shore and 179 inches at a height 2,800 feet up the mountain side. The following table gives the results of a partial analysis of the soils taken from these different districts:

Effect of rainfall upon composition of soils.

Land.	Average rainfall.	Chemical constituents of the soils.			
		Lime.	Potash.	Phosphoric acid.	Nitrogen.
	Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Dry	60	0.474	0.324	0.248	0.176
Wet	120	.248	.270	.243	.450

These figures indicate that soils derived from the same lava rocks vary extremely in their chemical composition, and that the chemical difference is the result of the different climatic conditions. The great excess of rainfall over the wet lands has removed the soluble lime and potash, and at the same time has largely augmented the amount of

nitrogen, which element is brought from the air and stored up in the soil in the accumulated organic matter. A more specific example is found upon the island of Hawaii in the districts of Hilo and Kau. Hilo is located upon the humid side of the mountain, and the Kau district lies on the side of limited rainfall. The rainfall and composition of the soils are as follows:

Effect of rainfall upon composition of soils.

District.	Average rainfall.	Chemical constituents of the soils.			
		Lime.	Potash.	Phosphoric acid.	Nitrogen.
	Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Kau (dry)	56	0.955	0.846	0.606	0.505
Hilo (wet)	180	.128	.257	.504	.840

In the Hilo district the rainfall ranges between 160 inches and 210 inches per annum. The table shows the great difference in the proportions of the important constituents in the soils of the two districts, all of which have been derived from the same basaltic lava rocks. The difference in the cane crops grown in the two districts is just as striking. In the Kau district the lands are highly productive when the rainfall is enough to support growth. In the Hilo district the yield of sugar per acre is little more than one-half the crop of Kau in normal seasons; and upon the higher lands in the district, where cultivation of cane has gone on for some ten or fifteen years, the soils are so badly washed out that they have ceased to produce remunerative crops, and great expense is being incurred to restore the depleted fertility. From these examples we see the results of an unusually large precipitation falling upon the ground year after year. Frequently in the Hilo district deluges of water carry the earth bodily into the sea, reddening the ocean a mile out from its shores. The analyses of the soils show that the soluble plant-food elements have been removed, while the crops testify that such is the case. According to the data furnished by Schuyler and Allardt, the Hawaiian plantations are striving to apply by irrigation from 200 to 260 inches of water per crop, with what results, according to the testimony of nature, will eventually be seen.

The writer has been endeavoring to obtain evidence in detail by means of tests made at the experiment station, showing the effects of the excessive use of water upon the soil itself and upon the chemical fertilizers that are applied for the use of the crop.

In the course of the tests made by means of the lysimeter for determining the loss of water when given amounts were applied by irrigation, determinations were also made in one of the series of tests showing the elements contained in the wasted water which had been removed from the soil. In the following example is shown the volume of water

that drained out of the soil with the amounts of the more chemical elements carried out in the water during a period of ninety days:

Fertilizing constituents leached from the soil by excessive irrigation.

Loss of water.	Constituents removed from soil per acre.		
	Lime.	Potash.	Nitrogen.
Gallons.	*Pounds.*	*Pounds.*	*Pounds.*
58,000	278	61	117

These amounts of the elements were taken out of the natural soil by the excess of water applied during the short period of ninety days. The water that is escaping from a field of newly cultivated ground differs greatly from the drainage water of a whole district whose surface is largely made up of undisturbed grass, forest, or other similar growths. The ground coverings save the soil from the direct action of the water, and where the subsoil has remained undisturbed for a great length of time the percolating waters have wrought out their own channels of escape to the substrata, and the results are that the water escapes very rapidly, but carries relatively little dissolved soil materials with it. It is just the opposite with water falling upon or being applied to freshly broken and cultivated soil. It reaches every particle, saturating and acting upon its soluble constituents, and, according to the length of time that the water occupies in passing through, is the amount of solid matter contained in the drainage. The great difference in the amounts of solid matter contained in general drainage waters and in waters escaping from a newly broken soil in a high state of cultivation in the same district is as follows:

	Per cent.
Solid matter in general drainage water	0.0537
Solid matter in water from fresh soil	.7200

These figures indicate that the amount and character of the solid matters contained in the drainage waters of a vast watershed can not be taken as showing the solid soil elements which are being leached out of cultivated areas by excess of water. It has also been observed that the water escaping from cropped fields that have laid still and have been irrigated regularly for a considerable length of time does not contain as much solid matter as was found in the first leachings from the fresh soil. In the course of time the water works its own minute channels of escape through cultivated grounds, when the water escapes more rapidly, but carries less material with it. In the lysimeter tests this action of the applied water in working down its own lines of escape became so very pronounced that the experiments had to be stopped until the drains were all renewed and the soil rendered homogeneous again.

The escaping water not only carries with it the elements of plant

food present in the natural soil; it also acts ruinously upon several of the elements contained in artificial fertilizers that are applied at great cost to growing crops. The following table shows the water and chemical elements contained in the water lost per acre during ninety days. In one test the ground was planted with cane; in the other the ground bore no crop.

Chemical constituents contained in drainage water.

Land.	Loss of water.	Loss of constituents per acre.		
		Lime.	Potash.	Nitrogen.
	Gallons.	*Pounds.*	*Pounds.*	*Pounds.*
Cropped land	57,250	467	73	325
Bare land	92,250	1,140	213	561

The first thing observed from these figures is the action of the growing crop in reducing the loss of water, and consequently of the fertilizing elements. The loss, however, especially upon the land bearing no crop, is enormous. Yet this loss is not greater than has been observed in the open field and on a large scale. In the district of Hilo, Hawaii, already spoken of, the lime content in 1 acre of soil to the depth of 1 foot is less than 4,000 pounds. In the dry district of Kau, on the arid side of the mountain, the lime content is not less than 35,000 pounds per acre to the same depth, thus indicating that some 30,000 pounds of lime per acre have been leached out by the great rains. The considerable amounts of nitrogen leached out require no explanation, as the soluble and wasteful behavior of the nitrates is well known, as also the action of nitric and hydrochloric acids in plundering the lime content of soils. These phenomena, then, exhibit very clearly the ruinous effects of excessive application of water upon natural soils and upon the artificial fertilizing elements that are applied to crops.

Effects of excess of water on crops.—The results to growing crops that follow heavy and continued rainfalls are matters of common experience and often causes of widespread loss. No fact is more thoroughly established in agricultural experience than this one: That while a moderate rainfall is indispensable to growing crops, an excess of rain is the cause of immediate loss in the crop and of damage to the soil. In the wheat districts of Europe every farmer knows what he may expect from a dry spring; but if the month of May is wet as well as cool he also knows that the yield may be cut down by one-third.

In the series of tests that were made at the Hawaiian Experiment Station to determine the amount of water that could be applied to the cane in furrows before leaching and loss of water took place concurrent observations were made upon the effect of applying different volumes of water upon the germination of the cane seed and the subse-

quent growth. The character of the soil of the three plats included in the test was the same. The cultivation and fertilization were also the same. The cane seed was all selected and each plat was planted the same day. At the time of planting and afterwards the plats received, respectively, 1 inch, 2 inches, and 3 inches of water per week and with the follwing results:

Plat 21.—One inch of water per week; cane found coming through the soil on the sixth day after planting.

Plat 23.—Two inches of water per week; cane coming through the ground the eighth day after planting.

Plat 25.—Three inches of water per week; cane coming through ten days after planting.

It is thus seen that the cane seed receiving 1 inch of water per week germinated and came through the ground four days in advance of the cane seed receiving 3 inches of water per week. The relative number of the cane seeds that grew in the plats receiving the different volumes of water is shown in the following table:

Number of plants germinated in plats receiving different quantities of water.

Plat.	Water applied weekly.	Seed—pieces planted.	Seed—pieces that grew.	Seed—pieces that died.
	Inches.			
No. 21	1	802	706	96
No. 23	2	802	698	104
No. 25	3	802	628	174

On October 1, four months after planting, the canes were all counted in each of the three plats, the number found being as follows:

Number of canes growing at the end of four months in plats receiving different quantities of water.

Date.	No. of plat.	Depth of water applied per week.	Number of canes in the plat.
		Inches.	
October 1	21	1	1,995
Do	23	2	1,701
Do	25	3	1,599

From the data contained in the previous tables and statements it is shown—

(1) That the larger the volume of water applied to the planted cane seed in excess of 1 inch in depth the greater was the time required in germination.

(2) The greatest number of cane seeds died where the largest volume of water was applied.

(3) The greatest number of canes was found four months after planting where the least volume of water was applied.

It is to be noted that the above data apply to the cane at the time of planting and during the early stages of growth. With greater development, and especially at the stage of maximum growth, the consumption of water will be considerably greater until 2 inches per week will be demanded.

In the germination of the cane seed or of any other seeds the supremely essential factor is the oxygen of the air. Without the presence of the air and a moderate amount of moisture germination can not take place. On the other hand, when the ground is filled with water and kept in a saturated state, the air normally present in wholesome soils is driven out and replaced by the water; consequently the first essential to a rapid germination and growth is removed. Again, in the presence of an excess of moisture and a dearth of oxygen the germination is not only slow, but it can be stopped after having begun, and the seedling dies. These principles are illustrated in the tests already cited, where it is seen that the cane seed which received the great excess of water not only was four days longer in coming through the ground, but that a relatively larger proportion did not come up at all, having died in the ground. The application of an excess of water can also create another condition highly detrimental to a rapid and healthy germination. Irrigation water, which comes either from high altitudes or from underground wells, is generally very much cooler than the soil to which it is applied. In the tests made the temperature of the soil to a depth of 6 inches was 88° F., while the water was 72° (the writer has found the temperature of some underground waters on the Hawaiian Islands to be 25° cooler than the air). The pouring on of a large excess of water of relatively low temperature immediately reduces the temperature of the soil. and thus makes another condition unfavorable to healthy germination and rapid growth. In cane-sugar countries, where the rainfall is liable to be considerable and the temperature of the soil is low at the time of planting, the cane seed will lie for weeks before coming up, and in unfavorable seasons much does not germinate at all.

In one series of tests conducted by the writer, in which it was sought to include all factors conducive to growth and to avoid any unfavorable conditions, the irrigation was begun and is being continued as follows: The seed was planted in dry and thoroughly cultivated and porous soil and sufficient water was applied to cover the ground to a depth of 1 inch. This amount was equal to a depth in the furrow, however, of 2.5 inches, which sank down and wet the soil to a depth of 6 or 8 inches below the seed bed. The application of 1 inch per week was repeated and continued for a period of four months. Not only at the time of germination, but even up to the end of three months after planting, the seed and the young cane could not consume anything like 1 inch of water per week.

Until the plant began to shade the ground considerable evaporation took place. The volume of water lost in this manner was much greater than that consumed by the young plant. This was clearly shown by the results of evaporation and transpiration tests. With the increased development of the cane its consumption of water was greater, but the increased foliage protected the soil against the sun, and the loss of water from the soil itself became less. This demand for an equal volume of water each week was maintained until the crop was four months old, when the ground surface was completely covered by the cane foliage. At this time the crop was rapidly adding to its substance. Cane stalks were well developed and the consumption of plant food and water was vastly augmented. In the fifth month of its age the appearance of the leaves showed that the cane required a somewhat increased weekly allowance of water, and this was confirmed by the moisture found in the soil, which was down to 18.5 per cent. The soil in question has a capacity for taking up 48 per cent of its own weight of water, and the effort is made to prevent the actual moisture in the soil from sinking below 20 per cent and from raising above 30 per cent, the conditions of growth being most favorable when the moisture present in the soil is equal to about one-half of its maximum water-holding capacity. The exceptions to this rule are controlled by the temperature. In cool weather and low soil temperature the water in the soil should be kept low; in warm growing weather the moisture in the soil should be higher, but the point of saturation should never be reached or growth is impeded or stopped. In the fifth month more water was applied, the amount being increased to 1½ inches per week. The cane could not bear the extra half inch every week, and alternate weeks only 1 inch was applied, until the greatly increased growth demanded not only 1½ inches weekly, but even 2 inches if the winds were very drying.

As the cane gets older its root system develops proportionately, running not only in all lateral directions, but deeper where the soil allows. It is therefore good practice to increase the volume of irrigation so that the soil moisture reaches as low as the roots penetrate. In fact, the moisture should be kept a little lower than the roots, in order to induce them to feed deeper. An extra irrigation of half an inch, and even an inch, may be given to be sure that the moisture content is maintained below. This moisture at a greater depth is not only required to cause the plant to feed deeper, but it is indispensable for the purpose of rendering the more insoluble matter of the subsoil soluble and ready for the future use of crops.

At the time this report is written the cane in the tests in question is ten months old. The cane stalks are some 8 feet in height, and the crop is so heavy that it lies nearly flat and almost shuts out the sun. During a week of warm, sultry weather it consumes 1.5 inches of

water. If the air is clear and warm, and a dry wind prevails, 2 inches per week are given; but if cool nights and average days prevail, only 1 inch of water is given per week. The cane is in perfect health and growth; the moisture is maintained in the soil, as attested by the analyses; and no water escapes, as indicated by the observation drains. The object in irrigating sweet soils with sweet water is to meet the demands of soil evaporation and of transpiration by the crop, and to maintain an equilibrium of moisture in the soil relative to its maximum water-holding capacity, and to avoid leaching and loss.

SOME GENERAL OBSERVATIONS.

In the course of annual visits of inspection made by the writer to all districts upon the several islands of the Hawiian group during the past five years, ample opportunities have been afforded to observe the methods of irrigation in general practice and the results that have followed the application of water. There are districts, such as have been already described, where the temperatures are high and the rainfall very small, and where crops could not be produced without the aid of irrigation. In most of these arid districts the soils are deep and of great fertility, which is largely due to the absence of heavy leaching rains, such as obtain in wet districts. The application of water to those deep, rich soils has resulted in the production of enormous crops. Those lands are still virgin so far as concerns the length of time they have been under cultivation, not more than four to eight crops having been taken off. It may be that the present methods employed in irrigation will in time injure the land. If there is any change in this respect it is not now evident. It is possible that overirrigation in certain localities, if not corrected, will render the lands nonfertile before the twentieth crop has been reached. The following paragraph is taken from the annual report of the present manager of one of the largest and most fertile plantations on Hawaii:

> It has come under our observation that the mechanical condition of the soil in the older fields, owing to the action of nitrate of soda (and heavy irrigation), is not as good as that of virgin fields immediately adjoining. * * * It is apparent that any water passing through a soil, and beyond the cane roots, carries with it a certain amount of soluble matter, whether it consists of fertilizers applied or natural fertilizing elements in the soil. Therefore any water beyond that taken up by the cane is engaged in a leaching process that is detrimental. Thus, in spite of the generous fertilizing that has been carried on upon this plantation, some of the older fields show a decrease in available potash and lime.

The plantation here referred to is new, none of its lands having produced more than five crops. Since the lands were cultivated and the cane crops heavily irrigated evidences of excessive irrigation have made themselves clear. When the water is applied to the lands on the higher levels in excessive quantities the excess percolates through into

the substrata, and reappears upon the surface of lands at lower levels. In this particular example numerous so-called "springs have broken out on the lands next to the sea since the irrigation of the fields above." Upon another island a manager of one of the plantations replied to the writer, in answer to questions: "Oh, yes; after every irrigation those gulches run a pretty good stream for the next twenty-four hours." The gulches in question are the low places to which the watersheds of the fields converge, and through which the excess of water applied in each irrigation finds its outlet to the sea. I have seen costly fertilizers, in bags, thrown into the ditches to be dissolved and distributed by the water, and consequently to be carried to the sea by the excess of water that found its way there. In another case the manager of the plantation said to the writer:

So much water used to be run onto this field that it seeped out after every irrigation into the deep ditch running across the bottom end of the field; from that ditch it was turned into the field below and used over again. But now we put on less than half the former quantity and irrigate oftener, and there is no waste.

In one other case the plantation manager remarked:

We have had wonderfully fine springs of water in our low gulches since those upper lands have been irrigated.

A few statements of a different kind have been received from plantation managers who were open to argument upon the methods of irrigation. One gentleman writes:

The recovery of that field of ratoons from the horrible yellow state in which you saw it, and the yield of sugar, were due to lessening the supply of water before it was too late.

Another manager wrote:

The half of the field which has received just one-half of the usual allowance of water is better cane and the juice is of better quality than the cane upon the other part of the field getting the old amount of water.

Unfortunately the number of these testimonials is small, most of the managers preferring to continue in the old way. A new factor, however, is beginning to operate in certain districts. So much land is being devoted to sugar cane, causing an increased demand for water, that the supply is already insufficient. It now appears that water will have to be very economically handled in order to make it cover increasing demands. Economy in use is, therefore, a factor with which the managers of our irrigation matters will have to deal, and when that is accomplished, the day of the scientific irrigator will have come.